

Incorporating Climate Change and Variability into Bulletin 17B LP3 Model

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The current techniques for flood frequency analysis presented in *Bulletin 17B* assume annual maximum floods are stationary, meaning that the distribution of flood flows is not significantly affected by climatic trends or long-term cycles (i.e. decadal variations). Observed trends in stream flows raise concern as to whether or not this assumption is valid. This paper considers how the *Bulletin 17B* framework might be modified to account for nonstationarity in flood records due to climate variability. In order to improve estimates/forecasts obtained using the LP3 model, the effects of climate variability may be incorporated into updated estimates of the mean, standard deviation, and perhaps the skew by regressing the LP3 parameters on climatic indices describing the Pacific Decadal Oscillation and Northern Atlantic Oscillation. The effects of climatic cycles occurring over a shorter time frame, such as El Niño, are averaged into estimates made using the procedures of *Bulletin 17B*. However, the effects of El Niño are likely to affect the magnitude of annual maximum stream flows, and thus would impact flood risk in a given year. El Niño effects are incorporated into forecasts by regressing the LP3 parameters on sea surface temperatures.

Introduction

It has been recognized that the Earth's climate is governed by a dynamic and forever changing system [Knox, 1984; NRC, 1998]. Climatic changes are evident in hydrologic conditions, such as increased rainfall and decreased temperatures. Several studies have considered the effects of El Niño on these variables (for example, Piechota and Dracup [1996], Guan et al. [2005], Regonda et al. [2005] and references therein). Kunkel et al. [1999] and Groisman et al. [2001] explore the relationship between heavy precipitation and high streamflows. For monthly data, Lettenmaier et al. [1994] observe strong trends in streamflows, mean temperature, temperature range, and precipitation at several stations in the continental United States. Trends in streamflows have also been investigated in numerous more recent studies (see for example, Kalra et al. [2006] and the references therein). Several studies have focused on changes in flood risk for the Upper Mississippi River Basin; a review of those studies is provided by Olsen et al. [1999]. This paper considers how current flood frequency procedures might be modified to account for possible nonstationarity in flood records due to climatic variability.

The current methodology for flood frequency analyses by U.S. federal agencies is presented in *Bulletin 17B* (B17) [IACWD, 1982]. B17 recommends fitting a log-Pearson type 3 (LP3) distribution to annual maximum flood series {Q(t)}. The recommended technique is to use the method of moments (MOM) to fit a Pearson type 3 (P3) distribution to the logarithms of the flood peaks, denoted {X(t)}. Estimates of the mean μ, standard deviation σ, and skew γ of the logarithms of the sample data are computed using traditional moment estimators. Additional procedures to adjust the sample moments and improve flood quantile estimates are also contained in B17. These recommended procedures assume annual maximum floods are stationary. In other words, it is assumed that the distribution of flood flows is not significantly affected by climatic trends or cycles [Olsen et al., 1999; Hirschboeck et al., 2000]. Observed trends in streamflows raise concern as to whether or not this assumption is valid [NRC, 1998; Franks and Kuczera, 2002].

Climatic patterns which may result in long-term variability in flood risk are the Pacific Decadal Oscillation (PDO) and the Northern Atlantic Oscillation (NAO) [Olsen et al., 1999; Garbrecht and Piechota, 2006]. These patterns exhibit low frequency variability with shifts that last on the order of decades. For the Upper Mississippi River Basin, Olsen et al. [1999] relate annual maximum flows to PDO and NAO using linear regressions. They found PDO and NAO explained little of the variation in flood peaks. Using nonparametric tests on monthly data for stations across the United States, Tootle et al. [2005] identified significant differences in streamflow between the cold and warm phases of both the PDO and NAO at several stations.

Another climatic pattern which would likely affect the magnitude of annual maximum stream flows is El Niño. However, these events occur over a relatively short time frame, generally 12 – 18 months, and thus are not expected to result in long-term changes in flood risk. For the Upper Mississippi River Basin, Olsen et al. [1999, p. 1511] observed that "as long as the frequency and intensity of El Niño events are not changing over time, flood frequency analysis naturally accounts for climate variability associated with El Niño events." Nevertheless, in terms of forecasting, it is likely that El Niño effects would impact flood risk in a given year. Using monthly data, Tootle et al. [2005] also considered the El Niño-Southern Oscillation (ENSO) and identified significant differences in streamflow between the cold (La Niña) and warm (El Niño) phases in Florida, the Southwest and the Pacific Northwest. The effects of PDO and NAO coupled with ENSO were also investigated. The influence of ENSO on streamflow has also been investigated by Jain and Lall [2001], Chiew and McMahon [2002], Kiem et al. [2003], Twine et al. [2005], and Tootle et al. [2006]. And several other studies have considered the use of ENSO indicators in probabilistic streamflow forecasts (for example, Piechota and Dracup, 1999; Hamlet and Lettenmaier, 1999; and Grantz et al., 2005).

Studies have also investigated nonstationarity in flood flows. For example, Olsen et al. [1999] perform a simple linear regression of flood flows on time. Stedinger and Crainiceanu [2001] compare a two-parameter log-normal distribution fit to annual maximum series to a log-linear model with a linear trend in the mean and a log-normal ARMA model of flood flows. Strupczewski et al. [2001] use the maximum likelihood method to estimate time-dependent parameters of a P3 distribution for annual maximum flood series. Coulibaly and Baldwin [2005] propose use of a dynamic recurrent neural network for prediction of nonstationary hydrological time series. Sveinsson et al. [2005] consider shifting mean models which assume a constant long-term mean about which the stochastic model moves from one "stationary" state to another. Several studies have considered use of Generalized Extreme Value (GEV) models with time-dependent parameters, including Coles [2001, p. 106] and El Adlouni et al. [2005].

This paper considers how to incorporate the effects of climate variability into updated estimates of the mean, standard deviation, and skew of the log-annual floods in order to improve estimates/forecasts obtained using the LP3 model recommended by B17. Time-dependent parameters could be employed to reflect observed trends in flood peaks, however, it is not clear this is appropriate. To relate nonstationarity in flood peaks to climate change, a more appropriate approach would be to regress the LP3 parameters on climatic indices describing, for example, the PDO and NAO. The effects of climatic cycles occurring over a shorter time frame, such as El Niño, are averaged into estimates made using the procedures of *Bulletin 17B*. However, the effects of El Niño are likely to affect the magnitude of annual maximum stream flows, and thus would impact flood risk in a given year. Therefore, it could be worthwhile to try to incorporate these effects into forecasts of the flood risk in any year which might effect reservoir flood-storage requirements.

The following section considers two approaches for incorporating El Niño forecasts into computations of flood risk with the LP3 distribution. The simplest is to divide past and future years into several categories based upon the value of El Niño or another climate index, and develop a frequency distribution for each category. A more sophisticated approach is to attempt to develop a relationship (perhaps described by a parametric function) relating climate indices to variations in the statistical properties of floods. As discussed below, each of these approaches has its advantages and disadvantages.

Incorporation of El Niño Effects

The Nino-3.4 sea surface temperature (SST) anomalies from the equatorial Pacific are a common indicator of El Niño events. SST time series are provided by the Climate Prediction Center at the website http://www.cpc.ncep.noaa.gov/data/indices/. To incorporate the effects of El Niño into flood frequency forecasts, a regression model can relate each parameter of the P3 distribution (μ, σ, and γ) to a three-month average of the SST anomalies observed each year. A model for the mean μ is:

$$\mu_t = \alpha + \beta c_t + \varepsilon_t \quad (1)$$

Here μ_t is the mean computed using the logarithms of all floods from the observed record available through time t, α and β are regression parameters, and ε_t is the independent model error. The El Niño effects are represented by c_t, which is the climate index (i.e. SST anomaly) observed in time t. Variations in the mean over time result from abnormal values of the climate index (SST). Other indices such as the Southern Oscillation Index and the Multivariate ENSO Index could also be employed [Piechota et al., 2006].

Using the model in eqn. (1), a one-year ahead forecast of the mean would be

$$\hat{\mu}_1 = \alpha + \beta \hat{c}_1 \tag{2}$$

wherein $\hat{c}_1$ is a forecasted value of the climate index (SST anomaly). Forecasts of SST anomalies are available from the Climate Prediction Center at the website: http://www.pmel.noaa.gov/tao/elnino/forecasts.html#enso. A similar approach could be used to update (forecast) the value of the standard deviation σ, and possibly the skew γ of the P3 distribution, such that the logs of the flood peaks would be modeled as $X_t \sim P3(\mu(t), \sigma(t), \gamma(t))$. The updated parameters would then be used to forecast flood risk for the next year. This is a reasonable approach to incorporate the effects of climate variability into forecasts used for water management such as dam or reservoir operation.

Coles [2001, pp. 105-8] recommends a similar approach to account for nonstationarity in annual maximum sea-levels due to El Niño. Let GEV(ξ, α, κ) denote the GEV distribution with location parameter ξ, scale parameter α, and shape parameter κ. Coles suggests modeling the annual maximum sea-level Z_t in year t as a function of the Southern Oscillation Index in year t, SOI(t), using the GEV distribution such that

$$Z_t \sim GEV(\xi(t), \alpha, \kappa) \tag{3}$$

where

$$\xi(t) = \beta_0 + \beta_1 \, SOI(t) \tag{4}$$

Coles notes that similar expressions could be used to model $\alpha(t)$ and $\kappa(t)$, although with limited data it would be difficult to estimate parameters for the model of $\kappa(t)$ with adequate precision.

Katz et al. [2002] suggest modeling the monthly maximum of daily precipitation by a GEV distribution in which the mean and standard deviation are modeled as linear functions of the mean sea level pressure. With this model, nonstationarity is expressed in terms of both the mean and the standard deviation, whereas a model such as eqn. (3) only allows changes in the mean.

A model wherein nonstationarity is expressed in terms of both the mean μ and the standard deviation σ is particularly appropriate for flood statistics. Using the LP3 model as recommended by B17, the logs of the flood peaks X_t could then be modeled as $X_t \sim P3(\mu(t), \sigma(t), \gamma)$ wherein $\mu(t)$ and $\sigma(t)$ are modeled as functions of a climate index such as SST. But one might believe that the coefficient of variation C_v of the flood distribution should remain constant over time. In this case, if the mean scales with changes due to El Niño, then there must be a corresponding change in the standard deviation. This could be captured by the model $X_t \sim P3(\mu(t), \sigma(t), \gamma)$, however, with limited data, it could be difficult to estimate additional parameters for $\sigma(t)$. Moreover, it is not clear that this would ensure a constant C_v. An alternative approach would be to use the model

$$X_t \sim P3(\mu(t), \sigma, \gamma) \tag{5}$$

where

$$\mu(t) = \alpha + \beta \, SST(t) + \varepsilon_t \tag{6}$$

Here the standard deviation and skew of X = ln(Q) are independent of time; as a result the coefficient of variation of Q will also be independent of time. This is a nice advantage that follows from modeling the logarithm of the flows. The parametric approaches discussed thus far also have the advantage that they add relatively few parameters to the standard model, all of which could be estimated by maximum likelihood or Bayesian methods. The simple model in eqns. (5) and (6) has only two extra parameters.

Instead of developing models of the distribution parameters, an alternative approach would be to categorize the flood events according to whether they occurred when the ENSO phase was warm, neutral, or cold. Separate distributions could then be fit to each of the three categories. This type of approach was employed by Hamlet and Lettenmaier [1999] in developing a probabilistic streamflow forecast model. Hirschboeck et al. [2000] discuss potential causes of mixed distributions which may be enhanced by ENSO-teleconnections. In essence, categorizing the flood series in this way is analogous to mixtures of distributions employed when floods arise from different types of events, such as snowmelt versus rainstorms (see Waylen and Woo [1982] or Stedinger [2000]). However, unless the individual categories are composed of events with distinctly different distributions, it would be best to develop one model for the entire flood series using eqns. (5) and (6) such that fewer parameters need be estimated and more data is available to do so. If one categorizes the data, how should one proceed if one category contains relatively few observations?

Overall, the model in eqns. (5) and (6) is a reasonable approach to incorporate climate variability due to El Niño into forecasts made using the LP3 model. This model is proposed for forecasting one year ahead for use in water management such as dam and reservoir operation. For longer term planning, the effects of El Niño are averaged into the flood frequency estimates obtained using the *Bulletin 17B* guidelines. However, for use in planning and the design of dams, levees and other water control structures, a similar approach may be used to incorporate the effects of climate change in the flood estimates. This is briefly discussed in the following section.

Incorporation of PDO and NAO Effects

Nonstationarity in flood peaks could be related to climate change by regressing the LP3 parameters on climatic indices, such as those describing the PDO and NAO, in the same fashion as suggested above for the incorporation of El Niño effects. Models which include indices for both PDO and ENSO could also be explored as several studies have indicated possible coupling of PDO with ENSO (for example, Tootle et al. [2005, 2006] and citations therein). Values of the PDO index are provided by the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington via the website: http://tao.atmos.washington.edu/pdo/. Values of the NAO index are available at the National Center for Atmospheric Research website: http://www.cgd.ucar.edu/cas/jhurrell/indices.html.

A problem with this approach, however, is that making forecasts of the LP3 parameters over a long enough time scale for planning and design would require reasonable forecasts of the PDO, NAO, or other selected indices over that time frame. Presently, the needed forecasts are not available with any precision. Hamlet and Lettenmaier [1999] propose assuming that the climatic variation is reflected in the historic record and that those patterns will persist into the future. Alternatively, Hirschboeck et al. [2000, p. 67] suggest basing future flood risk assessments on climatic periods in the historical record "characterized by the highest flood frequencies or magnitudes". These are two potential solutions, however, based on the research available at this time, it is not clear how to proceed. There is now general agreement that we will see anthropogenic climate change over the next few decades [Nakicenovic and Swart, 2000; Houghton et al., 2001; McCarthy et al., 2001], but how to transform that belief into a quantitative description of how flood frequency relationships will change is still an unresolved challenge. Will storms be more frequent, or just more intense? And how will changes in temperature, humidity, soil moisture, groundwater levels, and ground cover affect the risk of large floods?

Conclusions

Several studies have demonstrated the impact of climate variability on streamflows. The *Bulletin*'s assumption that observations are independent and identically distributed should be reconsidered, and the guidelines for flood frequency analysis contained in *Bulletin 17B* should be adapted to deal with nonstationarity in flood records. While the effects of climatic cycles occurring over a shorter time frame, such as El Niño, are averaged into estimates made using the procedures of *Bulletin 17B*, estimates/forecasts for reservoir operation and management obtained using the log-Pearson type 3 model might be improved using a simple parametric approach such as suggested here. Furthermore, estimates/forecasts which account for the effects of long-term cycles such as the Pacific Decadal Oscillation and the Northern Atlantic Oscillation should be particularly useful for longer planning horizons and design, but how to forecast the needed indices is not particularly clear at this time.

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